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Preprint typeset using L^AT_EX style emulateapj v. 04/03/99OFF-BEAM GAMMA-RAY PULSARS AND UNIDENTIFIED
EGRET SOURCES IN THE GOULD BELTALICE K. HARDING¹ AND BING ZHANG^{1,2,3}*Draft version December 4, 2000*

ABSTRACT

We investigate whether gamma-ray pulsars viewed at a large angle to the neutron star magnetic pole could contribute to the new population of galactic unidentified EGRET sources associated with the Gould Belt. The faint, soft nature of these sources is distinctly different from both the properties of unidentified EGRET sources along the galactic plane and of the known gamma-ray pulsars. We explore the possibility, within the polar cap model, that some of these sources are emission from pulsars seen at lines of sight that miss both the bright gamma-ray cone beams and the radio beam. The off-beam gamma-rays come from high-altitude curvature emission of primary particles, are radiated over a large solid angle and have a much softer spectrum than that of the main beams. We estimate that the detectability of such off-beam emission is about a factor of 4-5 higher than that of the on-beam emission. At least some of the radio-quiet Gould Belt sources detected by EGRET could therefore be such off-beam gamma-ray pulsars. GLAST should be able to detect pulsations in most of these sources.

Subject headings: stars: neutron; pulsar: general; gamma rays: pulsars

1. INTRODUCTION

The origin of the 170 unidentified gamma-ray point sources detected by the Energetic Gamma-Ray Experiment Telescope (EGRET) on board the Compton Gamma-Ray Observatory (CGRO) throughout its mission (Hartman et al. 1999) is one of the most intriguing questions of high-energy astrophysics. Grenier & Perrot (1999) found that some of the unidentified sources are significantly correlated with the Gould Belt of massive stars, a nearby galactic structure surrounding the Sun. The Gould Belt is an expanding disk of gas and young stars, most with ages less than 30 million years, inclined about 20° to the galactic plane. Recently, Gehrels et al. (2000) studied the spatial and flux distribution of the 120 steady sources in the third EGRET catalog and found that they divide into two groups: higher flux sources distributed along the galactic plane with latitudes less than 5°, and a new population of lower flux sources at mid-latitude which indeed seem to be associated with the Gould Belt, at a relatively nearby distance of 100-300 pc. The two groups also show significant differences in their spectra, with the low-latitude sources having average photon spectral index of 2.18 ± 0.04 and the mid-latitude sources having average photon index of 2.49 ± 0.04 . None of these sources have known counterparts at other wavelengths. Grenier & Perrot (1999) suggested that the Gould Belt γ -ray sources could be young pulsars, formed in supernova explosions of massive stars of the belt. However, the relatively soft spectra and luminosities of these sources, averaging $\sim 6 \times 10^{30} \text{ erg s}^{-1}$, are not characteristic of the known γ -ray pulsars detected by EGRET, which have spectral indices of 1.5 – 2.0, luminosities $10^{32} - 10^{34} \text{ erg s}^{-1}$ and 0.5-4 kpc distances.

Here, we show that the bulk of the Gould-Belt γ -ray sources could be pulsars if their emission is seen at large angles to their magnetic axes, such that we are missing

the bright, hard γ -ray beams but detecting only the off-beam emission. According to the polar cap model (e.g. Daugherty & Harding 1996 [DH96]), γ -ray emission occurs throughout the entire pulse phase. A synchrotron-pair cascade at low altitude radiates the hard on-beam emission in a hollow cone centered on the magnetic pole to produce the bright double-peaked pulses. Primary electrons continue to radiate curvature emission on open field lines to high altitudes beyond the cascade region, producing a lower level of softer off-beam emission. Due to the flaring of the dipole field lines, this emission may be seen over a large solid angle, far exceeding that of the main beams. Since the radio emission is expected to originate within ten stellar radii of the neutron star surface, it is quite probable to see off-beam γ -ray emission and miss the radio beam. Such off-beam or off-pulse emission may have been detected by EGRET in the Crab, Vela and Geminga γ -ray pulsars during non-pulse phases (Fierro et al. 1998). We show that this expected off-beam emission has the right characteristics (spectral index, luminosity and numbers) to account for the EGRET sources associated with the Gould Belt.

2. OFF-BEAM PULSAR EMISSION

2.1. Geometry

The basic geometry of polar cap emission, projected onto the stellar surface, is shown in Figure 1. The main beam of the γ -ray cascade emission zone is located along the edge of the hollow cone with opening angle θ_γ , centered on the magnetic axis, denoted by the dotted circle labeled γ . The altitude of this zone is about 1 - 2 stellar radii above the stellar surface (DH96, Harding & Muslimov 1998). The off-beam γ -ray emission zone is located at altitudes above the cascade emission zone, from several stellar radii to the light cylinder. Off-beam emission visi-

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ble to EGRET above 20 MeV is shown as a shaded region. The radio emission can have a core component, thought to be located at low altitude along the magnetic axis, and/or a conal component(s), thought to be located in a hollow cone at altitudes of tens of stellar radii (e.g. Rankin 1993). In the polar cap model, the radio emission originates from the secondary pair cascade. In Fig. 1, the possible location of radio conal emission with opening angle θ_R is shown as a dashed circle labeled R. The circles centered on the rotation axis, labeled ζ_1 and ζ_2 , denote the sweep in pulse phase of different observer lines-of-sight viewing on-beam and off-beam γ -ray emission respectively.

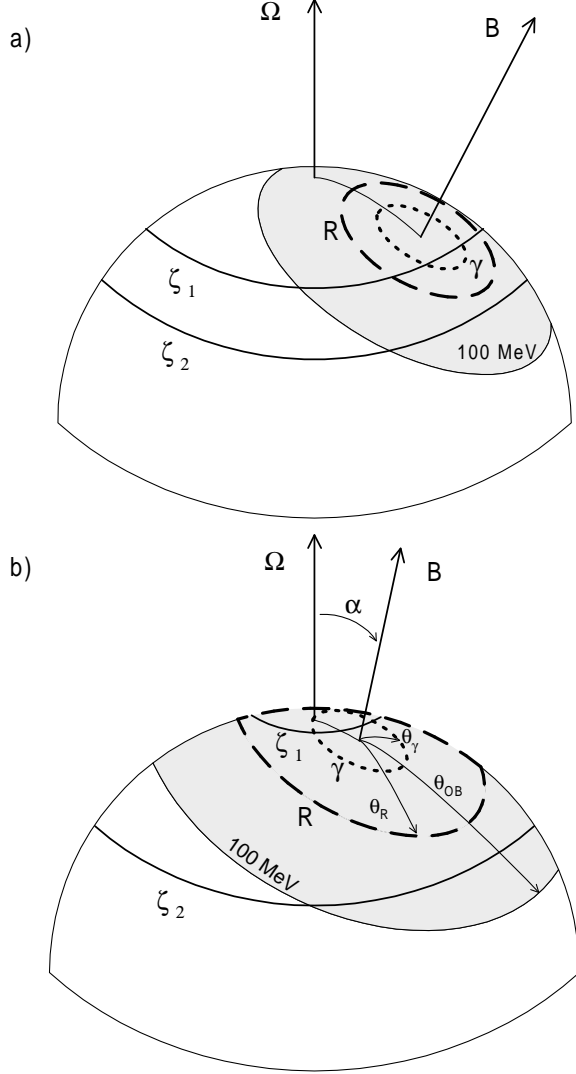


FIG. 1.— The geometry of the polar cap model projected onto the stellar surface. The dotted circle labeled γ is the main gamma-ray conal beam, the dashed circle is a conal component labeled R of the radio emission beam, and the circle enclosing the shaded region denotes the cone where the typical curvature radiation emission of the primary particles is 100 MeV. The shaded area is the above-100 MeV-emission area of the pulsar. The inclination angle between Ω and \mathbf{B} is α and ζ 's denote different lines of sight. The line-of-sight ζ_2 cuts off the main gamma-ray beam and misses the radio emission beam, and we identify such configurations as the off-beam pulsar candidates for the “Gould Belt” faint, soft, unidentified EGRET sources. (a) α not small: ζ_1 gives a typical Vela-type emission configuration; (b) α small: ζ_1 gives a typical Geminga-type emission configuration.

The off-beam gamma-ray emission is mainly produced by curvature radiation of the primary particles, well beyond the acceleration and cascade zone. For a certain inclination angle α and line of sight ζ , the off-beam emission zone, between $r_{\text{OB}}(\text{min})$ and $r_{\text{OB}}(\text{max})$, (or the corresponding $\theta_{\text{OB}}(\text{min})$ and $\theta_{\text{OB}}(\text{max})$) may be determined by geometry and the curvature radiation properties. The minimum height, $r_{\text{OB}}(\text{min})$, is the lowest height visible to a given line-of-sight and is defined by the radius at which the tangent to the last open field line, which is $\frac{3}{2}\theta$ for a dipole, where θ is the polar angle, points in the direction of the observer (which is also the outer edge of the off-beam γ -ray emission cone at that radius):

$$r_{\text{OB}}(\text{min}) \simeq \frac{c}{\Omega} \left[\frac{2}{3}(\zeta - \alpha) \right]^2 \quad (1)$$

For $P = 0.3$ s, and $\zeta - \alpha = 10^\circ$, we have $r_{\text{OB}}(\text{min}) \sim 19R$.

The maximum height at which EGRET-band emission (> 100 MeV) can be produced may be defined as the radius $r_{\text{OB}}(\text{max})$ along the last open field line where the curvature radiation photon energy $E_0 = 100$ MeV. The typical curvature photon energy is $E_0 = (3/2)(\gamma^3 \hbar c / \rho) = 322 \text{ MeV } \gamma_7^3 P^{-1/2} (r/R)^{-1/2}$ for dipolar field configuration, where $\gamma_7 \equiv \gamma/10^7$ is the primary particle Lorentz factor, ρ is the magnetic field radius of curvature, P is the pulsar period and r and R are the radii of the emission point and stellar radius, respectively. To be detected by EGRET, one thus requires

$$\gamma_7 > \gamma_7(100 \text{ MeV}) \equiv \gamma_{100} = 0.68 P^{1/6} (r/R)^{1/6}. \quad (2)$$

The expression for the Lorentz factor of a particle traveling along an open dipole field line and subject only to curvature radiation losses is (Harding 1981)

$$\frac{\gamma}{\gamma_0} = \left[1 + \frac{9}{8} r_e \theta^2 \frac{\gamma_0^3}{r} \ln\left(\frac{r}{R_0}\right) \right]^{-1/3}, \quad (3)$$

where $r_e = e^2/mc^2$ is the classical electron radius and γ_0 is the initial Lorentz factor at R_0 , the radius of the acceleration zone. Using Eqn (3), Eqn (2), and the expression for the last open dipole field line, $\theta^2 = (r\Omega/c)$, we have the following equation for $r_{\text{OB}}(\text{max})$,

$$\left[\frac{\gamma_{100}(r_{\text{OB}}(\text{max}))}{\gamma_{0,7}} \right]^{-3} = 1 + \frac{9}{8} \frac{r_e}{c} \Omega \gamma_0^3 \ln\left(\frac{r_{\text{OB}}(\text{max})}{R_0}\right) \quad (4)$$

where $\gamma_{0,7} \equiv \gamma_0/10^7$. Finding the root of this equation yields values of $r_{\text{OB}}(\text{max})$ for different values of $\Omega = 2\pi/P$, γ_0 and R_0 , which will be limited by the light cylinder distance, $\sim r_{\text{LC}}/\sin \alpha$ in short-period pulsars. For $P = 0.3$ s, $\gamma_0 = 2 \times 10^7$ and $R_0 = 2R$, one finds $r_{\text{OB}}(\text{max}) = 48R$.

2.2. Relative Observability

The relative opening angle, $\theta_{\text{OB}} \sim (\Omega r_{\text{OB}}(\text{max})/c)^{1/2}$, of the “100 MeV cone” with respect to the on-beam γ -ray cone, $\theta_\gamma \sim (\Omega r_\gamma/c)^{1/2}$, is: $\theta_{\text{OB}}/\theta_\gamma \simeq (r_{\text{OB}}(\text{max})/r_\gamma)^{1/2}$. For a fixed α , the relative detectability of the off-beam pulsars and the gamma-radio plus Geminga-like pulsars is

(note that only geometric effects, but no luminosity selection effect is taken into account):

$$D(\alpha) = \frac{\cos(\text{Max}[0, \alpha - \theta_{\text{OB}}]) - \cos(\text{Min}[\pi/2, \alpha + \theta_{\text{OB}}])}{\cos(\text{Max}[0, \alpha - \theta_{\gamma}]) - \cos(\text{Min}[\pi/2, \alpha + \theta_{\gamma}])} - 1 \quad (5)$$

Assuming a random distribution of α , the relative detectability of the off-beam pulsars and the gamma-radio plus Geminga-like pulsars is (Emmering & Chevalier 1989):

$$D = \frac{(1 - \cos \theta_{\text{OB}}) + (\pi/2 - \theta_{\text{OB}}) \sin \theta_{\text{OB}}}{(1 - \cos \theta_{\gamma}) + (\pi/2 - \theta_{\gamma}) \sin \theta_{\gamma}} - 1. \quad (6)$$

Given typical values $P = 0.3$ s, $r_{\gamma} = 2$, and assuming emission along the “last open field line”, one gets $\theta_{\text{OB}}/\theta_{\gamma} \sim 5$ and $D \sim 4$ according to eq.[6]. Figure 2 shows the dependence of both $r_{\text{OB}}(\text{max})$ and D on pulsar period. If we regard Geminga and PSR 0656+14 (the strongest gamma ray pulsar candidate) as the on-beam gamma-ray pulsars in the Gould Belt, we expect that there might about 8 off-beam gamma-ray pulsars, a sizable portion of the 20-40 Gould Belt unidentified EGRET sources (Grenier et al. 2000). The luminosity selection effects will modify this number, but the above estimate suggests that at least some of the Gould Belt sources could be off-beam γ -ray pulsars.

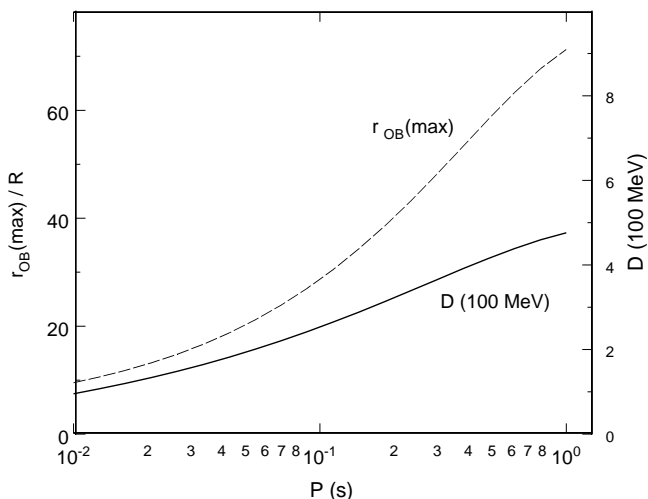


FIG. 2.— Solutions for the maximum radius of off-beam emission, $r_{\text{OB}}(\text{max})$, from Eqn. (4) and for the detectability of off-beam relative to on-beam emission, D , Eqn (6), as a function of period, P .

Figure 1a and 1b show two different possibilities for observer orientation relative to the spin and magnetic axes. In Fig. 1a, $\zeta_1 > \alpha$ so that the line-of-sight cuts outside magnetic axes, seeing both bright rims of the γ -ray cone (and thus a double-peaked γ -ray profile) and the radio cone. Assuming the trailing radio component is missing, the broad band pulse profiles of the Vela pulsar and PSR B1046-58, with γ -ray pulse phase separation $W = 0.4$ and phase difference between the radio and leading γ -ray pulses of $\delta\phi = 0.12$, are consistent with this picture over a large $\alpha - \zeta$ phase space as long as α is not too large. In Fig. 1b, $\zeta_1 < \alpha$ so that the observer cuts between the spin and magnetic axes, seeing both bright rims of

the γ -ray cone (and thus a double-peaked γ -ray profile), but missing or grazing the radio cone. Such a configuration might describe Geminga-like pulsars. Thus, the phase space $\text{Max}(0, \alpha - \theta_{\gamma}) < \zeta < \text{Min}(\pi/2, \alpha + \theta_{\gamma})$ comprises radio-loud γ -ray pulsars and Geminga-like pulsars, both with double-peaked γ -ray profiles. The phase space $\alpha + \theta_{\gamma} < \zeta < \pi/2$ or $0 < \zeta < \alpha - \theta_{\gamma}$ contains the off-beam γ -ray pulsars having single peaked γ -ray profiles. Thus, we expect that the majority of the γ -ray pulsars detected in the Gould Belt will be radio quiet.

2.3. Luminosity and Spectrum

Since the energy loss rate for curvature radiation, $\dot{\gamma}$,

$$\dot{\gamma} = \frac{2}{3} \frac{\gamma^4 e^2}{mc^5} \left(\frac{c^2}{\rho} \right)^2 = 6.6 \times 10^9 \gamma^4 P^{-1} (r/R)^{-1}, \quad (7)$$

declines with height, the luminosities of the off-beam sources then mainly depend on $\dot{\gamma}[r_{\text{OB}}(\text{min})]$. A rough estimate of the relative luminosities of the on-beam and off-beam γ -ray emission is then

$$\frac{L_{\gamma}(\text{on})}{L_{\gamma}(\text{off})} \sim \frac{\dot{\gamma}(\text{on})}{\dot{\gamma}(\text{off})} \sim \left[\frac{\gamma_0}{\gamma[r_{\text{OB}}(\text{min})]} \right]^4 \left(\frac{r_{\text{OB}}(\text{min})}{r_{\gamma}} \right). \quad (8)$$

The maximum Lorentz factor of the primaries is (Zhang & Harding 2000)

$$\gamma_0 = 1.4 \times 10^7 P^{-1/4} (\cos \alpha)^{1/4}, \quad (9)$$

which is $\gamma_{0,7} \sim 1.9$ for typical values. Using Eqn (3), Eqn (8) and Eqn(1), for $P = 0.3$,

$$\frac{L_{\gamma}(\text{on})}{L_{\gamma}(\text{off})} \sim 80, \quad (10)$$

consistent with the typical luminosity of the Gould Belt sources.

Polar cap cascade simulations generally confirm the approximate results derived above. A simulation run for the parameters of the Vela pulsar, using the cascade code developed by DH96, give the brightness and model spectra of γ -ray emission as a function of $\zeta - \alpha$, shown in Figures 3 and 4 respectively. The contrast between on-beam and off-beam emission will be smaller for longer period pulsars. Small values of $\zeta - \alpha$ cut through the bright synchrotron core of the cascade, where the spectrum is a hard power law of index -2 with a high-energy cutoff above 1 GeV due to electron-positron pair production. For increasing values of $\zeta - \alpha$ the line-of-sight falls off the main beam, views higher-altitude emission and the luminosity decreases. However, the tail of high-altitude cascade curvature emission extends to large values of $\zeta - \alpha$ and allows the off-beam pulsars to be visible over a large solid angle. Figure 4 shows that the off-beam emission spectrum is much softer in the EGRET range, because the high-energy cutoff falls well below 1 GeV. The energy of the cutoff decreases with increasing $\zeta - \alpha$, as $r_{\text{OB}}(\text{min})$ increases and critical curvature photon energy E_0 , which now defines the cutoff, decreases. The spectrum of the off-beam emission in the EGRET band appears very soft because the E_0 is around 100 MeV. Power law fits to the off-beam model

spectra between 0.1 and 1 GeV (an example is shown in Figure 3) give photon indices in the range 2.2-3.0, consistent with what is observed for the Gould Belt sources.

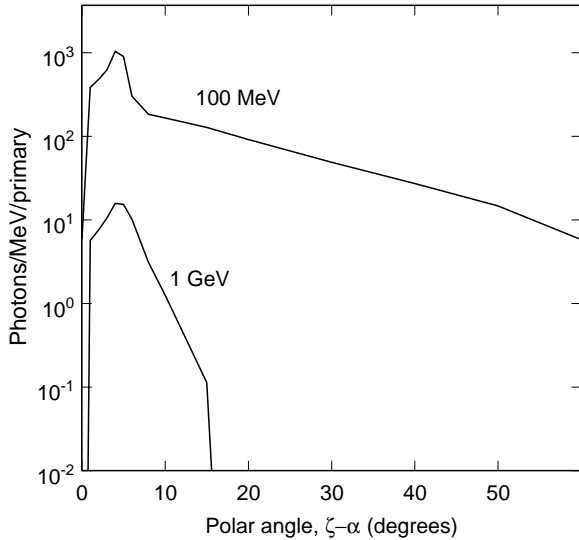


FIG. 3.— Distribution of γ -ray emission at 100 MeV and 1 GeV as a function of polar angle to the magnetic axis, $\zeta - \alpha$ for parameters of a Vela-type pulsar (cf. Fig. 4).

Given the relative luminosity of off-beam pulsars calculated from Eqns (7- 10), we can estimate absolute luminosity and the number of sources detectable by EGRET and GLAST. Using the predicted γ -ray luminosity, $L_\gamma(\text{on}) \simeq 5 \times 10^{32} \text{ erg s}^{-1}$, of a pulsar with $P = 0.3 \text{ s}$ and $B = 2 \times 10^{12} \text{ G}$ from a polar cap cascade (Zhang & Harding 2000, Eqn [60]), an average luminosity for an off-beam pulsar would be $L_\gamma(\text{off}) \simeq 6 \times 10^{30} \text{ erg s}^{-1}$. With an out-of-plane limiting point source sensitivity of $\Phi_{\text{EGRET}} = 6 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$ (Hartman et al. 1999), we estimate that EGRET can detect off-beam pulsars out to a limiting distance of $d_{\text{lim}} \simeq 260 \text{ pc} (\Omega_{\text{OB}})^{-1/2}$. Using Eqn (6) and the ratio $\theta_{\text{OB}}/\theta_\gamma \sim 5$, the average solid angle for off-beam emission is $\Omega_{\text{OB}} = 4\pi[(1 - \cos \theta_{\text{OB}}) + (\pi/2 - \theta_{\text{OB}}) \sin \theta_{\text{OB}}] = 3.4 \text{ sr}$. This gives a limiting distance for EGRET detection of off-beam pulsars as $d_{\text{lim}} \simeq 140 \text{ pc}$, about halfway through the Gould Belt. Assuming the supernova rate in the Belt derived by Grenier (2000) of $75 - 95 \text{ Myr}^{-1} \text{ kpc}^{-2}$, there would be about 23 - 29 neutron stars of age $\lesssim 5 \text{ Myr}$ within 140 pc of the Sun, about 8 of which could be detected as off-beam pulsars with a beaming factor of $\Omega_{\text{OB}}/4\pi \simeq 0.27$. This estimate is consistent with the above relative detectability estimate derived above based on geometry. The GLAST out-of-plane sensitivity to point sources having a cutoff at 1 GeV is $2 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$ (Digel, private comm.), which would allow GLAST to detect off-beam pulsars out to a distance of $d_{\text{lim}} \simeq 240 \text{ pc}$, most of the way through the Belt, and will be able to detect pulsations of those off-beam pulsars within 150 pc. Therefore, GLAST should be able to detect pulsations in all of the off-beam pulsars that EGRET detected as point sources.

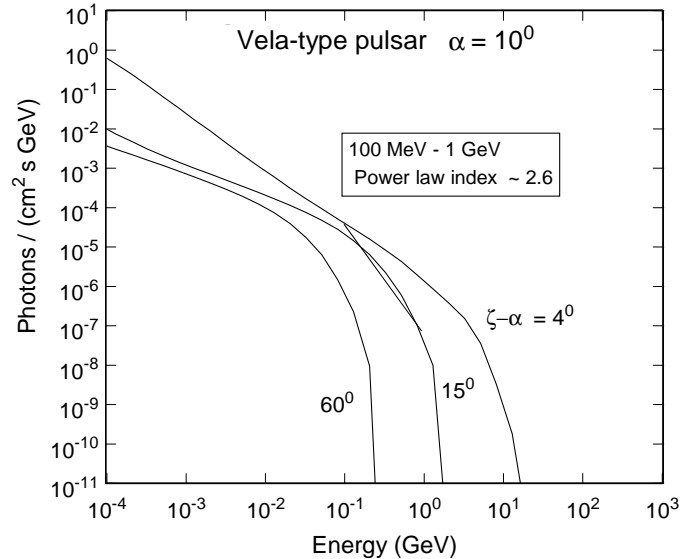


FIG. 4.— Model cascade spectra for different observed lines of sight, ζ 's. Typical Vela-type pulsar parameters, $P = 0.1 \text{ s}$, $B = 4 \times 10^{12} \text{ G}$ and $\alpha = 10^0$ are adopted. The $\zeta - \alpha = 40^\circ$ curve is for a typical on-beam pulsar, and the $\zeta - \alpha = 15^\circ$ and $\zeta - \alpha = 60^\circ$ curves are off-beam pulsar spectra. Notice that the off beam spectra are intrinsically fainter than the on-beam spectrum, and have a high-energy cut off at lower energies. A power law fit of the $\zeta - \alpha = 15^\circ$ spectrum from 100 MeV to 1 GeV gives a spectral index 2.65 ± 0.57 , consistent with the values observed from the unidentified ‘‘Gould Belt sources’’.

3. CONCLUSION

With the polar cap cascade geometry inferred from the known gamma-ray pulsars, we find that there is a large phase space for which the line-of-sight misses both the main gamma-ray beam and possibly the radio beam, but still cuts across a much broader, fainter gamma-ray beam produced by the curvature-radiation cooling of the primary particles. We identify such off-beam γ -ray pulsars as candidates for the new population of the unidentified EGRET sources associated with the Gould Belt. The off-beam polar cap cascade emission exhibits the low luminosity and soft spectrum in the EGRET band that is characteristic of the observed Gould Belt sources. A rough estimate indicates that the off-beam sources might be $\sim 4 - 5$ times more detectable than the on-beam sources due to the larger solid angle of the off-beam emission. A more accurate prediction of the fraction of off-beam γ -ray pulsars in the Gould Belt will require modeling of the pulsar population and luminosity selection effects. However, since EGRET detects all favorably oriented on-beam pulsars and a large fraction of off-beam pulsars in the belt, luminosity selection effects may not be a dominant factor. GLAST will be able to detect pulsed emission from these sources, and the pulse shape should be a broad single-peaked profile.

Off-beam emission is not expected in outer gap models (Yadigaroglu & Romani 1995, Cheng & Zhang 1998), which predict that most low-latitude ($|b| < 5^\circ$) unidentified EGRET sources in the plane are radio-quiet, Geminga-like pulsars. Thus, the radio-quiet outer-gap pulsars will be on-average as luminous in γ -rays as the radio-loud pulsars. This is in contrast to our prediction that po-

lar cap radio-quiet pulsars (at least those detected within a few hundred pc) should be on average less luminous in

γ -rays than radio-loud pulsars.

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